

AT THE INTERFACE OF QUANTUM AND GRAVITATIONAL REALMS

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Abstract In this talk I review a series of recent conceptual developments at the interface of the quantum and gravitational realms. Wherever possible, I comment on the possibility to probe the interface experimentally. It is concluded that the underlying spacetime for a quantum theory of gravity must be non-commutative, that wave-particle duality suffers significant modification at the Planck scale, and that the latter forbids probing spacetime below Planck length. Furthermore, study of quantum test particles in classical and quantum sources of gravity puts forward theoretical challenges and new experimental possibilities. It is suggested that existing technology may allow to probe gravitationally-modified wave particle duality in the laboratory,

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Introduction

The purpose of this written version of the talk given at the “Mexican Meeting on Mathematical and Experimental Physics (Colegio Nacional, 10-14 September 2001)” is to briefly review some of the conceptual developments at the interface of the quantum and gravitational realms. The version presented here primarily confines to the contributions I have made, and is by no means intended as a review of this developing field. I am also happy, when possible, to point reader’s attention to the relevant experimental literature.

Non-commutative Nature of Spacetime and Gravitationally-Modified Wave Particle Duality

Setting the Stage: Quantum Measurement with Gravitational Effects Ignored.

The experimental foundations of quantum mechanics reside in the *in principle* lower limit on the extent to which the unavoidable disturbance that the position and momentum measurements carry can be reduced.¹ This circumstance arises from the experimental implication of the photoelectric effect. It tells us that the energy carried by a light beam is not a continuous variable. Its intensity can only be changed in discrete units of $\hbar\omega$, where ω is the angular frequency of the probing light beam. This is encoded in fundamental commutators, such as:

$$[x, p_x] = i\hbar, \quad [x, y] = 0. \quad (1)$$

In configuration space, a solution of the above commutators is:

$$p_x = \frac{\hbar}{i} \frac{\partial}{\partial x}. \quad (2)$$

The operator p_x carries with it non-renormalizable eigenfunctions of the form

$$\psi(x) \sim \exp\left(\frac{ip_x x}{\hbar}\right). \quad (3)$$

However, integrating over different-momenta eigenfunctions one may obtain well-defined and normalizable wave packets that describe space-localizable particles. Now let λ be the spatial periodicity of $\psi(x)$. That is, $x \rightarrow x \pm \lambda$, advances the phase of $\psi(x)$ by $\pm 2\pi$. Then, we find that a particle of momentum p_x carries with a de Broglie wave length:

$$\lambda_{dB} = \frac{h}{|p_x|}. \quad (4)$$

In a commutative spacetime this lies at the heart of the quantum-mechanical wave particle duality.

Quantum Measurement with Gravitational Effects Incorporated.

The usual measurement process in quantum mechanics ignores any gravitational effects that may be inherent in it. Such effects become important in quantum gravity because, in general, there is an *unavoidable* change in the energy-momentum tensor associated with the collapse of a wave function.² Consequently, quantum measurements of spatio-temporal locations of events cannot ignore inherent gravitational effects.

These effects, we hasten to add are intrinsic to the events under consideration. In the first approximation, they do not directly refer to the background curvature [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12].

When gravitational effects in a quantum measurement process are incorporated it is found that there is an *in-principle and unavoidable* non-commutativity of the position and temporal measurements. Furthermore, the fundamental commutator undergoes a change of the form [12]:

$$[x, p_x] = i\hbar \left[1 + \epsilon \frac{\lambda_P^2 p_x^2}{\hbar^2} \right], \quad (5)$$

where

$$\lambda_P = \sqrt{\frac{\hbar G}{c^3}}, \quad (6)$$

and ϵ is a number of the order of unity (to be set to unity, now onwards). Given Eq. (6), the introductory discussion contained in “*Setting the Stage: Quantum Measurement with Gravitational Effects Ignored*” immediately implies that wave particle duality must suffer a fundamental change at the Planck scale. For one-dimensional motion, the change in wave-particle duality takes the form [13, 12]:

$$\lambda = \frac{\bar{\lambda}_P}{\tan^{-1}(\bar{\lambda}_P/\lambda_{dB})} \quad (7)$$

In the above equation we have defined, $\bar{\lambda}_P = 2\pi\lambda_P$. It is readily seen that in the low-energy limit the gravitationally modified wave length λ reduces to the well-known de Broglie wave length. In the Planck regime, however, something surprising, and welcome, happens. The gravitationally modified wave length λ saturates to (4 times, with $\epsilon = 1$) the Planck length. A similar result was later obtained by Bruno, Amelino-Camelia, and Kowalski-Glikman [14] (Also, see important observations of Padmanabhan in Refs. [15, 16]). Theoretically, this result may be interpreted as that no particle wavelengths are available to probe space-time below the Planck length distances (λ_P^2 areas, and λ_P^3 volumes). Moreover, this saturation also suggests that in some sense the relativity, special and general, must suffer changes so that length contractions below λ_P do not occur.

Theoretically, one is, therefore, called upon to develop a relativity that carries not only an inertial-observer independent velocity, i.e. c , but also a similarly independent length scale. The latter may be identified with

$\epsilon\lambda_P$. Amelino-Camelia has already undertaken the task of building such a modification to the relativity theory [17].

Experimentally, the derived saturation of λ , implies freezing of neutrino oscillations at the Planck energies, and carries several phenomenological implications [13]. However, the phenomenological implications may not be confined to early universe alone, as we now argue.

Superconducting quantum interference devices (SQUIDS), when cooled sufficiently below the critical temperature, may carry temperature-tunable superconducting currents with total superconducting mass

$$m_s \sim f(T) N_a m_c, \quad (8)$$

behaving as one quantum object (under certain circumstances). In Eq. (8), $N_a \approx 6 \times 10^{23} \text{ mole}^{-1}$, $m_c \approx 2 \times 0.9 \times 10^{-27} \text{ gm}$, and $f(T)$ encodes fraction of the available electrons that are in a superconducting Cooper state at temperature, T . Sufficiently below the critical temperature, $f(T)$ may approach unity. The temperature-tunable, m_s , can easily compete with Planck mass,

$$m_P = \sqrt{\frac{\hbar c}{G}} \approx 2.2 \times 10^{-5} \text{ gm}. \quad (9)$$

Thus, SQUIDS carry significant potential to probe wave-particle duality near the Planck scale. The theoretical and experimental problem that remains to be attended is to devise an experiment that invokes m_s , and not m_c .

Quantum Test Particles in Classical Sources of Gravity

Principle of equivalence with classical test particles in classical source of gravity has been verified to a remarkable accuracy, see, e.g., [18]. In this section we devote our attention to quantum test particles when the source of gravity is treated as a classical background.

The quantum behavior of a mass eigenstate in the classical source of gravity is well studied in the pioneering experiments on neutron interferometry [19, 20]. In recent such experiments an apparent violation of the principle of equivalence seems evident at roughly a part in one thousand [20]. If this result is not due to a yet unknown systematic error, then quantum mechanical motion of neutron in classical source of gravity poses serious theoretical challenge for its understanding [21, 22].

In atomic interferometry [23] the principle of equivalence is confirmed to a few parts in 10^9 .

To study the possibilities that quantum test particles offer to study gravitational field let's us first note that the local gravitational potential in the solar system carries two sources: (a) Solar-system sources, such as Earth, (b) Cosmological sources, such as the local super-cluster of galaxies. The former, on the surface of Earth, when measured in dimensionless units is, -7×10^{-10} , and varies as $R_{\oplus}/(z + R_{\oplus})$ — where z is the vertical distance from the surface of the Earth, and R_{\oplus} is Earth's radius. While the latter can be estimated to be roughly 3×10^{-5} — see, Ref. [21]. It is roughly constant over the solar system.

Potentials of the type "a" induce not only gravitational forces, but they also are also responsible for observable gravitationally-induced phases and the accompanying quantum interference effects. The type-b potentials are essentially force free, and they have the net effect of red-shifting local clocks. However, an experiment that seeks to study a possible violation of equivalence principle must treat such potentials with due care. In particular, given a violation of equivalence principle, the type-b potentials acquire a *local* observability. Quantum system — modeled after flavor-oscillation clocks [24, 25, 26, 27, 28, 29, 30] — appear to be most sensitive experimental probes for type-b potentials. There is now a significant and growing literature on the subject of flavor-oscillation clocks and I refer to the just cited list of references for the involved details.

Quantum Test Particles in Quantum Sources of Gravity

The next level of theoretical and experimental sophistication is called upon when one treats both the sources and the test particles as quantum objects. The example of the former is provided by a SQUID in a linear superposition of two counter-propagating super-currents [31]. An example of the latter is once again a system of flavor-oscillations clocks.

In the absence of a complete theory of quantum gravity, it is a non-trivial theoretical task to model the gravitational field of a quantum source of gravity. Yet, in the weak field, non-relativistic, regime the gravitational field may simply be taken as a quantum linear superposition of configurations with classical counterparts. To our knowledge, not even a preliminary analysis exists on the subject. However, as is apparent, such a theoretical undertaking is likely to prove a fruitful playing ground on the interface of gravitational and quantum realms.

Spatial and Temporal Fluctuations in Spacetime Foam

Amelino-Camelia has argued that *spatial* fluctuations of the space-time foam can be experimentally probed in gravity wave interferometers. This is a new and unexpected observation and may provide direct evidence for quantum-gravity induced effects [32, 33].

Complementing Amelino-Camelia's work, Kirchbach and I have put forward a thesis that the observed matter-antimatter asymmetry may arise from asymmetric space-time fluctuations and their interplay with the Stückelberg-Feynman interpretation of antimatter [34]. The thesis also argues that the effect of spacetime fluctuations is to diminish the fine structure constant, $\alpha = e^2/\hbar c$, in the past. Recent studies of the QSO absorption lines provide a 4.1 standard deviation support for this prediction [35, 36, 37]. It is entirely possible that the empirical data on the fine structure constant has already detected first signatures of the quantum-gravity induced spacetime fluctuations.

Concluding Remarks

Towards building a quantum theory of gravity, the interface of the gravitational and quantum realms is a rich conceptual and experimental arena. Here, theorists and experimentalists alike may play with much profit. In this talk I have outlined mostly my personal contributions. It is apparent that the underlying spacetime for a quantum theory of gravity must be non-commutative, that wave-particle duality suffers significant modification at the Planck scale, and that the latter forbids probing spacetime below Planck length. Furthermore, study of quantum test particles in classical and quantum sources of gravity puts forward theoretical challenges and new experimental possibilities.

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Notes

1. This remark applies equally well to any set of canonically conjugate variables.
2. Such a collapse may be associated with a position measurement, or position measurements of different components of a position vector.

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